Coherent Synchrotron Radiation via Strong Longitudinal Focusing
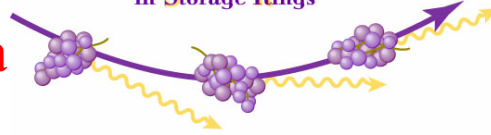
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Outline

- Coherent IR radiation in SR with fsec e-beam

- Strong Longitudinal Focusing (SLF) concept

- CSR "wake-field" & IFEL for SLF

- Stability criteria for fsec e-beam in SR

- Results of simulations

- Implications for IR SR source

➔ Conclusions

Coherent IR radiation in SR with fsec e-beam

- fsec e-beam radiates coherently at $\lambda < \lambda_c = 2\pi\sigma_s$

  $\lambda_c = 18 \ \mu m$ for 10 fsec RMS e-beam duration

- Intensity of IR radiation in proportional to N_e/μ–bunch

  $N_e \approx 6 \cdot 10^6$ for 1 pC charge/bunch (~ 5 μa/bunch)

  i.e. mWs of SIR become kWs of CIR

- What is needed - stable fsec e-bunches in SR

  ➔ suppression of microwave and CSR instabilities
  ➔ large number of μ–bunches (~ 20,000)
  ➔ low orbit compaction factor $\alpha_C < \sigma_s / (C\sigma_E / E)$
  ➔ strong longitudinal focusing for compress the bunches

The key for the concept of CSR IR source source is to create and to sustain electron bunches with femtosecond duration in the storage ring.

The electron bunches in the modern storage rings typically have RMS duration of tens to hundreds of psec. The reason behind the bunch lengthening and the growth of the energy spread is well known - it is the microwave instability caused by the longitudinal wake-fields and by coherent synchrotron radiation. The dominant obstacle is the wake field caused by coherent synchrotron radiation. The coherent synchrotron radiation causes wake-fields (to be exact, the forward fields) exceeding those caused by vacuum chamber by many orders of magnitude. Consequently, the effective impedance is much larger for sub-picosecond electron beams than for traditional tens-of-picosecond beams. In modern storage rings the longitudinal focusing does not play any significant role in the development and saturation of microwave instability as indicated by popular Boussard criterion which is identical to the Keil-Schnell criterion derived for a coasted beam, i.e. for the case without longitudinal focusing. This effect can be explained by the weakness of longitudinal focusing in existing storage rings, in other words that $Q_s \ll 1$, where is the tune of synchrotron oscillations.

Concept of Strong Longitudinal Focusing (SLF)*
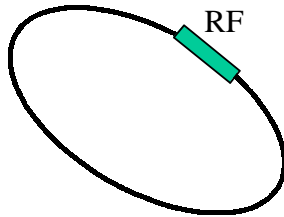
Microwave instability is due to Wake Field -> energy spread and bunch length growth

Peak Current threshold (Boussard's Criterion)

$$I_{peak} \cong \frac{2\pi\alpha_c E}{e(Z_n/n)}\left(\frac{\sigma_E}{E}\right)^2$$

Low synchrotron tune:
Fast MW instability:

$$Q_s \cong \sqrt{\frac{h_{rf}\alpha_c|eV_{rf}|}{2\pi E}}$$

$$Q_s \sim 0.001 - 0.01 << \xi_{MW}$$

Strong longitudinal focusing with $Q_s \sim 1$ suppresses microwave instability !!!

* *V.N.Litvinenko*, "On a Possibility to Supress Microwave Instability in Storage Rings using Strong Longitudinal Focusing", Proc. of ICFA Workshop on Nonlinear and Collective Phenomena in Beam Physics", Arcidosso, Italy, September 2-6, 1996, AIP Conference Proceedings 395 (1997) 275
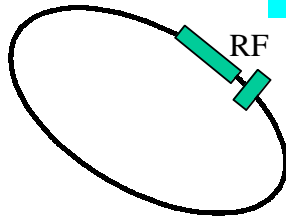

Strong Longitudinal Focusing

Boussard's Criterion does not work for:

$$Q_s \geq \xi_{mw} \approx \frac{I_{peak} Z(\lambda)}{2E/e}\frac{\alpha_c C}{\lambda}; \ \tau_{inc} = \frac{1}{\xi_{mw} f_o}$$

$$s_{n+1} = s_n + \alpha_c C\delta_n; \delta_{n+1} = \delta_n \cdot (1-\xi_d) - \frac{eV_{rf}(s_{n+1})}{E_o} + \Delta\delta_{SR}$$

$$V_{rf}(s) = eV_o \sin(k_o s + \varphi_o) + eV_1 \sin k_1 s$$

Small synchrotron oscillations: $X = \begin{bmatrix} s \\ \delta \end{bmatrix};$

$$s = v_e(t - t_o(z)); \delta = \frac{E-E_o}{E_o};$$

$$M_{s/cell} = \begin{bmatrix} 1 & \alpha_c C \\ -k_{rf}\dfrac{eV_{rf}}{E_o} & 1 - k_{rf}\alpha_c C\dfrac{eV_{rf}}{E_o} \end{bmatrix}$$

$$\mu_s = 2\pi Q_s; \cos(\mu_s/M) = Tr[M_{s/cell}] = 1 - k_{rf}\alpha_c C\frac{eV_{rf}}{2E_o}; \ \beta_s = \alpha_c C/\sin(\mu_s/M).$$

$Q_s \sim 1$

Requires either astronomical voltage from a regular RF system
OR
Short wavelength RF - *read inverse mm-FEL*

The strength of the longitudinal focusing is proportional to the value of *dV/dt*, i.e. the use of 0.25-1 mm RF wavelength enhances the focusing by three orders of magnitude compared with conventional RF systems. To get *Qs* = 0.31 with a mm-wave RF systems for the Duke storage ring with E_o =1 GeV, C =107.46 m, =3·10⁻³, it is sufficient to provide a voltage of:
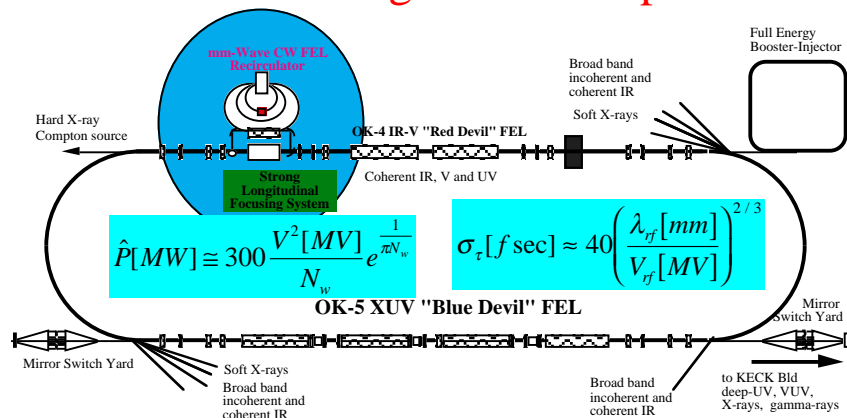
$$V_{rf}[MV] \cong \lambda_{rf}[mm]$$

Using inverse mm-FEL as RF system for strong longitudinal focusing has many advantages: an example

mm-Wave CW FEL Recirculator

Full Energy Booster-Injector

Broad band incoherent and coherent IR

Hard X-ray Compton source

Soft X-rays

OK-4 IR-V "Red Devil" FEL

Strong Longitudinal Focusing System

Coherent IR, V and UV

$$\hat{P}[MW] \cong 300 \frac{V^2[MV]}{N_w} e^{\frac{1}{\pi N_w}}$$

$$\sigma_\tau[f \sec] \approx 40 \left(\frac{\lambda_{rf}[mm]}{V_{rf}[MV]} \right)^{2/3}$$

OK-5 XUV "Blue Devil" FEL

Mirror Switch Yard

Mirror Switch Yard

Soft X-rays
Broad band incoherent and coherent IR

Broad band incoherent and coherent IR

to KECK Bld deep-UV, VUV, X-rays, gamma-rays

An example of the inverse FEL RF system
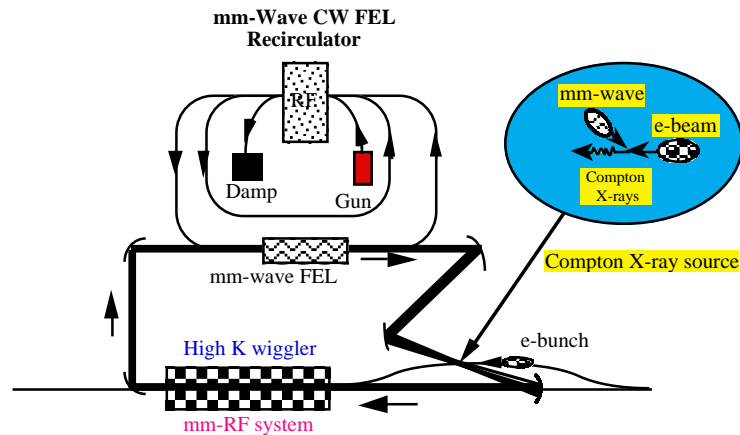
mm-Wave CW FEL Recirculator

RF

Damp   Gun

mm-wave FEL

High K wiggler

mm-RF system

e-bunch

mm-wave

e-beam

Compton X-rays

Compton X-ray source

CW mm-wave FEL Re-circulator

Energy in FEL, Ee [MeV]	4 - 8
Peak current in the FEL, A	10 - 20
FEL wavelength, mm	0.25 - 1
Number of passes	2 - 4
Pulses rep-rate [MHz]	2.8 - 22
Average beam current, A	0.05 -0.1
Normalized emittance [π mm.mrad]	50
Wiggler period, cm	10, 12
Wiggler gap, cm (max)	5
Number of periods	10
Kw	0.5-2
FEL gain, % (typical)	10-20
FEL efficiency, %	1-3
Energy recovery efficiency, %	~95
Average FEL power, kW	1 - 10
Peak intracavity power, GW	0.1 – 1

JLab IR Demo - Is operational example
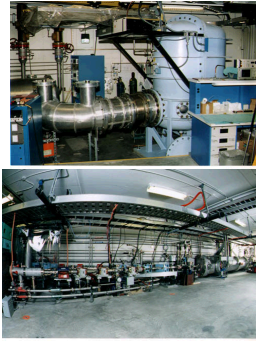
Average Power	~2 kW
Wavelength range	3-6.2 μm
Micropulse energy	up to 70 μJ
Pulse length	0.5-1.7 ps
PRF [MHz]	74.85, 37.425, 18.7
Bandwidth	0.3-2%
Amplitude jitter	<10% p-p
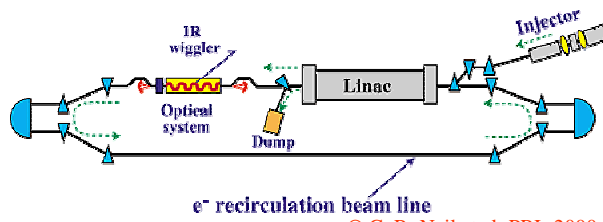
FEL BEAMLINE

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$$\hat{P}[MW] \cong 300 \cdot V_{rf}^{2}[MV] \cdot e^{\frac{1}{\pi N_w}} / N_w$$

Helical electromagnetic wiggler for mm-RF system

Total length [m]	3.0
Number of periods:	3
Period, λ_w [m]	1.0
Aperture [cm]	16
Magnetic field [kGs]	0 - 5
K_w	0 - 46.5
Maximum current	2.0 kA
Number of turns per pole:	2 x 10
mm-RF voltage [MV]	0.95[a]- 3[b]

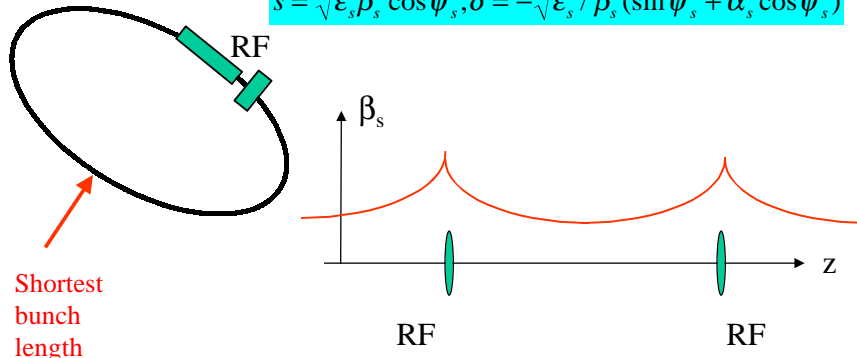[a]at P_{peak} = 100 MW;[b] at P_{peak} = 1 GW

Strong Longitudinal Focusing

Small synchrotron oscillations:

$$\beta_s = \frac{C}{\sin \mu_s};$$

$$s = \sqrt{\varepsilon_s \beta_s} \cos \psi_s; \delta = -\sqrt{\varepsilon_s / \beta_s} (\sin \psi_s + \alpha_s \cos \psi_s)$$

RF

β_s

z

Shortest
bunch
length

RF

RF

IFEL mm-wave RF

- Provide compensation for huge SCR wake

$$\left| \frac{dV_{wake}}{dt} \right| \leq \left| \frac{dV_{rf}}{dt} \right|$$

- Non-linearity of the synchrotron oscillation stabilize CSR micro-wave instability

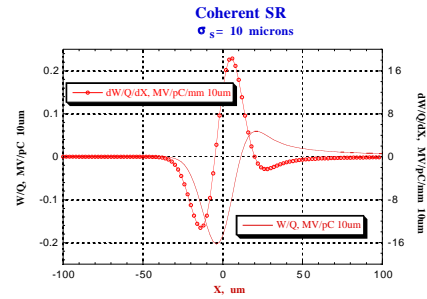$$I_{peak} \sim \frac{16\pi^3 E}{eZ(\sigma_l)} \cdot \frac{Q_s}{\alpha_c} \cdot \frac{\sigma_l}{C}$$

For fsec e-bunches Coherent SR wake-field is much stronger that that of the vacuum chamber

Wake field of damping ring
Note: scale is in V!
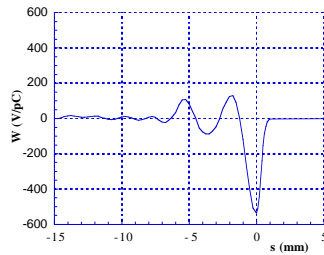
CSR wake field for e-beam with
Duration of 33 fsec RMS
Note: scale is in MV!

Stability Criteria for fsec e-bunches

With strong longitudinal mm-wave focusing , the micro-wave instability can be suppressed by de-coherence (Landau damping) caused by the anharmonicity of the synchrotron oscillations. The approximate criteria for the threshold of microwave instability for fsec bunches are*:

$$I_{peak} \sim \frac{4\pi^5 E}{eZ(\sigma_l)} \cdot \frac{Q_s}{\alpha_c} \cdot \frac{\sigma_l^3}{C \cdot \lambda_{rf}^2}$$

$$I_{peak} \sim \frac{16\pi^3 E}{eZ(\lambda)} \cdot \frac{Q_s}{\alpha_c} \cdot \frac{\sigma_l^2}{C \cdot \lambda}; I_{peak} \sim \frac{16\pi^3 E}{eZ(\sigma_l)} \cdot \frac{Q_s}{\alpha_c} \cdot \frac{\sigma_l}{C}$$

* V.N.Litvinenko, O.A.Shevchenko "Physics of femtosecond electron beams in storage rings", in preparation
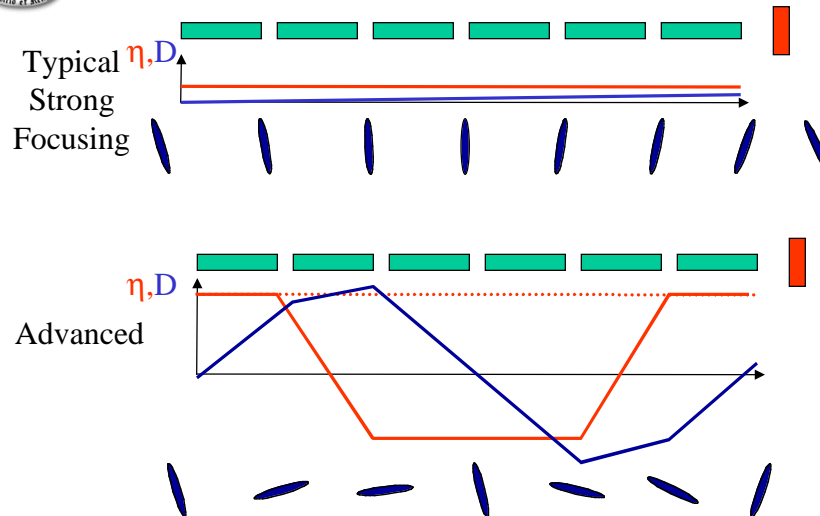
Advanced system

- Advance system has shot e-bunch only in few places where it is needed
- The integrated CSR wake-field reduces and the larger bunch currents can be compressed to fsec duration
- This mode is attainable in a ring where low-α is the result of alternating sign of η-function

Longitudinal dispersion

Typical Strong Focusing

η, D

η, D

Advanced

Strong Longitudinal Focusing

Small synchrotron oscillations:
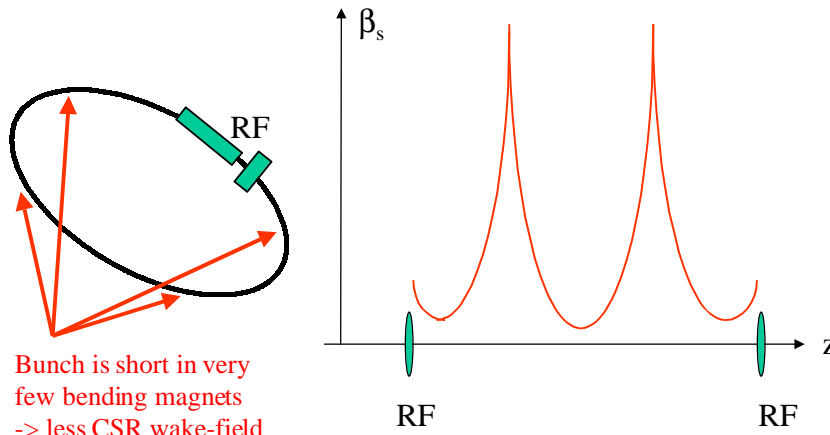
Bunch is short in very few bending magnets -> less CSR wake-field

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Numerical Simulations

Two computer codes for simulations: Electrons are represented by macroparticles. The typical number of macroparticles, *N*, used in tracking ranges from 5,000 to 10,000. A macroparticle is described by its energy, longitudinal position, transverse positions and momenta. Each macroparticle is tracked for a large number of turns. On each turn it interacts with RF cavities, magnetic lattice, wakefields, and coherent synchrotron radiation. The macroparticle is also subjected to quantum fluctuations of the synchrotron radiation and radiation damping defining the natural energy spread and the bunch length . The standard longitudinal wake-field and the field of coherent synchrotron radiation are calculated as the direct sum of the fields induced by individual macroparticles.

To reduce shot noise, we assumed that each macroparticle is a Gaussian cluster with RMS length of 1 μm (3 fsec). The wakefield is calculated in a number of locations (*i = 1,m; m* is from 1 to 16) around the arcs and the energy kick is applied to each macroparticle depending on its location in the bunch. After passing the arcs, each macroparticle interacts with RF system. This process, described by the following equations, is repeated each turn:

$$s^{i+1}{}_n = s^i{}_n + \alpha_c C \delta^i{}_n / m; \quad \delta^{i+1}{}_n = \delta^i{}_n \cdot (1 - \xi_d / m) - \frac{eW_{total}\left(s^{i+1}{}_n\right)}{E_o} + \Delta\delta_{SR} / \sqrt{m}; \ \{i = 1, m\};$$

$$W_{total}(s) = \frac{Q}{N} \sum_{n=1}^{N} W_o(s, s^{i+1}{}_n); \quad \delta^{m+1}{}_n = \delta^m{}_n - \frac{eV_{rf}\left(s^m{}_n\right)}{E_o}$$

Parameters used for tracking of longitudinal dynamics

Standard parameters	
Electron beam energy, GeV	0.75
Circumference, m	107.46
Radius of curvature, m	2.1
Revolution frequency, MHz	2.78
Frequency of standard RF, MHz	178
Voltage, standard RF, kV	700
Natural energy spread	0.0435%
Losses per turn, kV	12.4

Variable parameters	
Focusing (λ=0.25-1 mm) RF, GHz	300- 1,200
Voltage, focusing RF, MV	0 - 2
Orbit compaction factor, α_c	$8.6 \ 10^{-3}$ - $1 \ 10^{-5}$
Max number of macro particles	20,000
Number of turns	0 - 20,000
Interactions with wake per turn	40
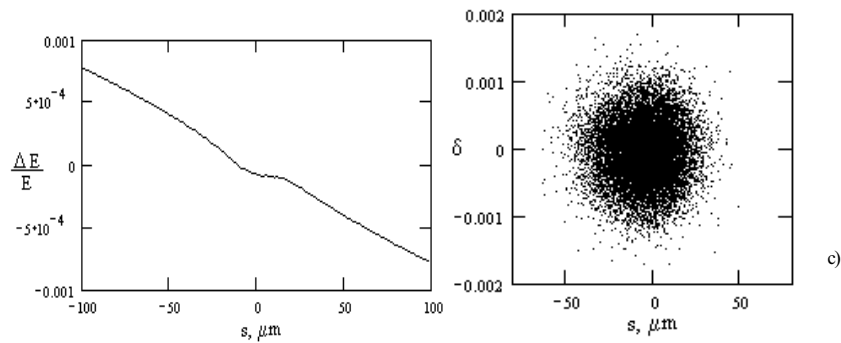
$$Q_{th} = 5.0 \text{ pC}, \ V_{1mm}= 1 \text{ MV}, \ \alpha_c= 10^{-4}, \ \sigma_t= 47 \text{ fsec}$$
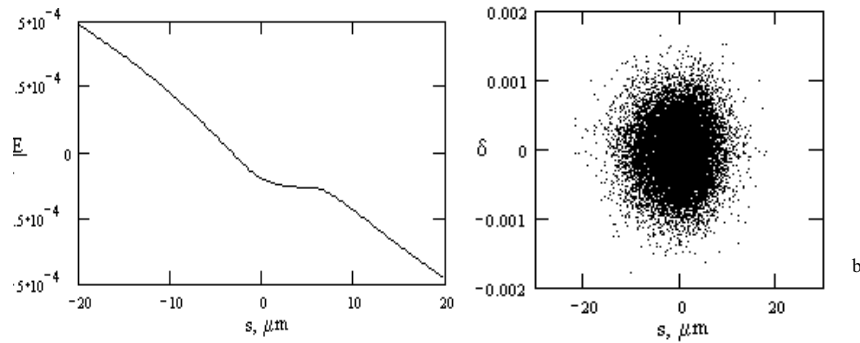
$Q_{th} = 1.3$ pC, $V_{1/3mm} = 1$ MV, $\alpha_c = 0.33 \cdot 10^{-4}$, $\sigma_t = 14.7$ fsec
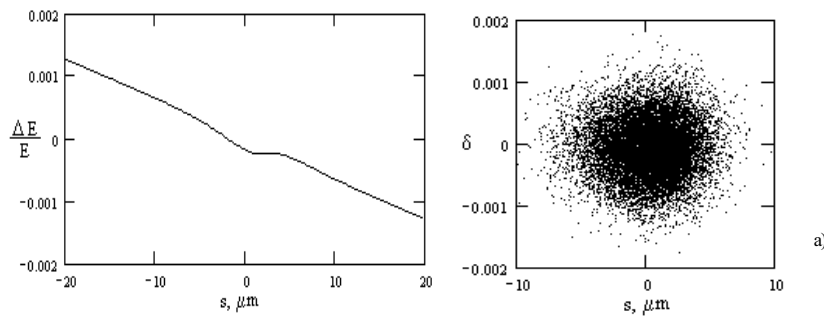
$Q_{th} = 1.0$ pC, $V_{1/4mm} = 2$MV, $\alpha_c = 0.25 \cdot 10^{-4}$, $\sigma_t = 11.2$ fsec

Time structure for a CSR IR source
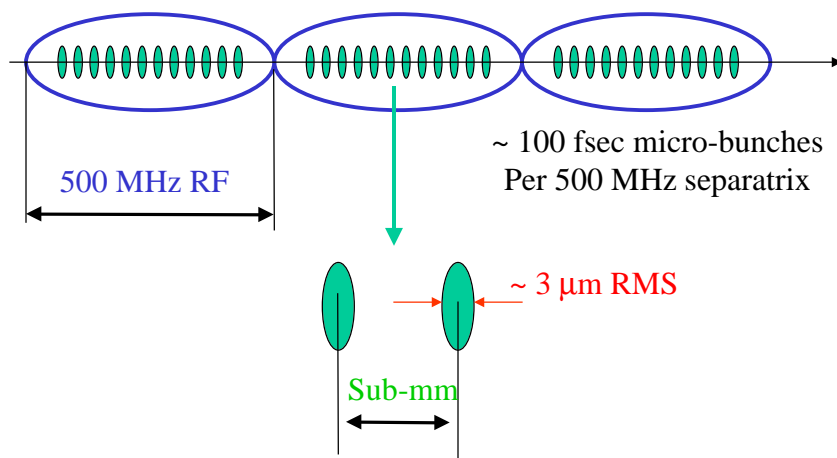
~ 100 fsec micro-bunches
Per 500 MHz separatrix

500 MHz RF

~ 3 μm RMS

Sub-mm

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kW CSR IR ring source

Circumference ~ 50 m   Energy ~ 0.5-1 GeV
mm-waves ~ 0.25 mm   Number main bunches ~ 100
Number of μ-bunches ~ 10^4 Beam current ~ 60 mA
e-bunch duration ~ 10 fsec

CW mm-wave FEL

500 MHz RF

IR wiggler
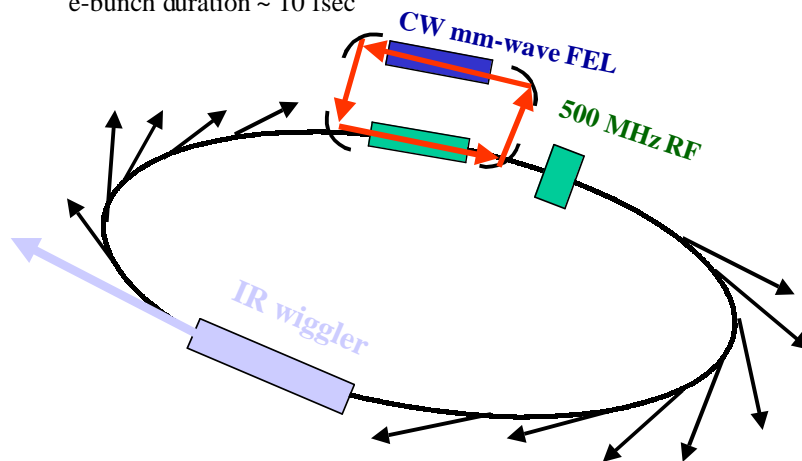
Conclusions

- A compact CSR IR source with kW level of power is feasible

- Significant part of the cost (~40%) will be in the mm-wave FEL for advanced RF system

- Acknowledgements:
    - Berndt Müller (Duke University)
    - Ying Wu (Duke University)
    - Oleg Shevchenko (BINP & Duke University)